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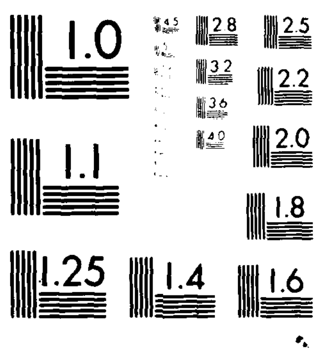

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September 1980

DCIEM Report No. 80-R-45

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DIGITAL HAND-HELD TEMPERATURE MONITOR

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ABSTRACT

A hand-held non-invasive monitoring instrument has been designed, constructed and tested to allow core temperature measurements to be obtained from human subjects who have swallowed a temperature-sensing radio transmitter (radio pill). This instrument uses a simple AM radio for a receiver, digital circuitry to decode the received signal and a four-digit LED module to display the temperature. The unit, which is battery-powered, can be held in one hand while an antenna probe is swept over the abdomen of the subject until a continuously audible signal is generated by a piezoelectric sound source, indicating reception. The digital display then presents the body core temperature in tenths of a degree Celsius.

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INTRODUCTION

Hypothermia and hyperthermia are major factors affecting the safety, performance, and comfort of personnel operating in adverse thermal environments (1). Diver hypothermia is a problem during diving operations in cold water in the ocean or during experimental dives in hyperbaric chambers. Hyperthermia is a problem in hot environments such as those experienced by helicopter or aircrew personnel on hot sunny days. A simple method for routine monitoring of body core temperature is the use of a swallowable temperature-sensing radio transmitter (2). Although the radio pill technique is not new, the pill developed at DCIEM (1,3,4) is inexpensive, easy to calibrate and disposable (since recovery is not required after use). Furthermore, the pill is more acceptable to subjects for long term application than is the rectal probe which has been known to cause mild discomfort (5,6). The radio signals transmitted by the pill can be decoded by suitable instrumentation to give the core temperature directly.

Although it is possible to obtain a continuous indication of core temperature, in many instances it is only necessary to obtain the temperature periodically. This can be done with a small portable hand-held temperature readout which can be held against the body when measurements are required; for example, with divers, before diving and after surfacing. The originally developed DCIEM hand-held readout (7) utilized analogue electronic circuitry but, because of the dc averaging technique used, the accuracy and response were limited. Spurious RF signals also caused problems for the analogue meter movement.

This report describes an improved version of the hand-held readout unit, using digital circuitry for decoding the radio pill signal and light emitting diodes (LEDs) for displaying the temperature.

RADIO PILL

The temperature sensing radio pill consists of a transistor, thermistor, capacitor, inductor and a battery. This comprises a blocking oscillator and RF transmitter which are contained in an oil-filled gelatin capsule that is protected by a thin coating of an inert medical grade silicone rubber (to prevent the pill contents from exposure to the body fluids). The circuitry and its component values are shown in Figure 1.

The thermistor (a temperature dependent resistor) controls the pill burst period which is proportional to the temperature of the surrounding area or cavity. Typical calibration curves from several pills produce parallel lines which can be normalized by a variable frequency offset (Figure 2).

The measurement of the burst period of a typical pill is shown in Figure 3. Although the true relationship between temperature and burst period is hyperbolic, the data points obtained from 30°C to 40°C, which are in the region of interest, are approximately linear. Hence, temperature changes around 37°C can be determined from a measurement of the pill burst period.

DIGITAL HAND-HELD TEMPERATURE MONITOR

The pill output consists of a burst of wide band RF in the AM radio frequency range. This signal can be detected and demodulated by an ordinary portable AM radio receiver and can be heard through the radio's speaker and counted to obtain a period measurement which is proportional to temperature.

Figure 4 shows the block diagram of the digital temperature monitor designed to obtain the pill temperature using a digital period measuring technique. In order to measure the period of the bursts accurately and reliably, the amplified signal from an AM radio is converted into square waves. The special purpose integrated circuit which measures the period of the square waves uses control and reference signals produced by supporting circuitry and hardware. The main blocks in Figure 4 (Receiver/Amplifier, Pulse Shape Network, Local Oscillator, Timing Circuit and Counter) and the packaging of the temperature monitor will now be described in detail.

Since analogue and digital circuitry were incorporated within the unit, two separate power supplies were required. This was accomplished by using a +9 volt alkaline battery as the primary source for the analogue circuitry and a +5 volt regulator to supply power for the digital circuitry (Figure 5A).

a) Receiver/amplifier

The receiver section consists of a small inexpensive portable AM radio in which the pill signal is detected with a ferrite core antenna. The input (front end) of the radio has been decoupled to suppress reception from any local radio stations present in the area by altering the tuning of the detector and first IF amplifier stages. In order to minimize space and conserve power, the driver and audio portions of the radio were removed.

The pill signal from the radio receiver is amplified by a quad operational amplifier (National Semiconductor LM 324). Since only a positive power supply (Figure 5A) is used, two separate inverting and non-inverting stages of amplification are used, as shown in Figure 5C, to achieve a gain of 1000X (60 dB). The amplifier signal then goes into a pulse shaping network.

b) Pulse Shape Network

In the pulse shaping network (Figure 5C), the pill burst is converted into a square wave using a monostable multivibrator (National Semiconductor MM74C221N) functioning in a one-shot mode. This monolithic complementary MOS integrated circuit uses an internal flip-flop which is initially held low and, upon application of the first positive transition of the burst waveform, is set to the "1" state (Figure 6). Once fired, the output level is independent of further transitions of the input and is a function of the external timing components C1 and R1. The voltage across the capacitor (C1) increases exponentially for a period of T=1.1R1*C1, and is followed by a resetting of the flip-flop by the comparator, causing in turn, a discharge of the capacitor and resetting of the output level to the low state "0". Since the burst period varies with temperature, optimum performance is achieved by selecting C1 and R1 to produce a 50% duty cycle at 37°C. This extension of the signal for a predetermined period of time reduces false triggering caused by RF interference or transient pickup.

The digitally encoded signal (output A in Figure 5) is used to control a slave oscillator which will produce an intermittent audible signal on a piezoelectric transducer. This indication of the received signal is generated only when the positive terminal of the operational amplifier (National Semiconductor LM 741 in Figure 5B) is held high. The frequency of the oscillator is set to 4.0 kHz.

c) Local Oscillator

The local oscillator acts as the clock for the counter circuit, at a frequency determined from the slope of the curve of temperature versus pill burst period. A frequency of 8.895 kHz, set by the selection of R2 and C2 (Figure 5D), is required to determine the temperature using the pill of Figure 1. The oscillator is the second half of the dual monostable multivibrator MM74C221 (used for the pulse shape network) and is set for astable operation. The oscillation is accomplished by charging capacitor C2 through resistor R2 from pin 4 (MM74C221) which is the inverse Q output ($\bar{Q}$ in Figure 5C). The capacitor charges exponentially until the upper trigger threshold is reached; at this point, the astable multivibrator toggles output B to its active high state. The inverse Q output changes its level to the low state which discharges the capacitor until its lower threshold voltage is reached. At this point, the multivibrator toggles output B back to its original state and the cycle repeats. The charge and discharge times and, consequently, the pulse frequency, are independent of the supply voltage.

d) Timing Circuit

The timing circuit (Figure 5E) provides the Intersil ICM 7217 counter with store and load cycle commands (Figure 7). These are produced by a divide-by-ten counter (National Semiconductor MM74C160) and a dual monostable multivibrator (MM74C221). The digitally-encoded radio pill pulses from the pulse shape network (output A) are counted by the MM74C160 and on the tenth pulse, a "carry" (output E) is generated. A track-and-hold switch (SW1), when depressed, enables the "carry" output to clock the first monostable multivibrator's inverse Q output to its low state (store cycle, output D). The first multivibrator and the store cycle output returns to its high state after an interval determined by C3 and R3. During this transition of the store cycle output, the second multivibrator toggles to its high state (load cycle, output C) for an interval determined by the values of C4 and R4.

e) Counter

The Intersil ICM 7217 performs the measurement of the pulse period and controls the operation of the monitor and display. The ICM 7217 contains a four-digit presettable up/down counter, four input lines for thumbwheel switches and decoder drivers for the seven-segment LED displays (Figure 8).

Measurement of the pulse period is initiated by the load cycle pulse (input C). A high level loads the three-digit pill calibration code from the thumbwheel switches into the counter. This code presets the up/down counter to an initial temperature offset with 0.1°C resolution. The return of the load cycle pulse to a low level enables the counter to count downward at the local oscillator frequency (input B). The final count attained, when a low level store pulse (input D) is received, is equivalent to the radio pill temperature. The store pulse transfers the temperature to the seven-segment LED display. On the transition from a low to a high store pulse, a load cycle is generated and another measurement is initiated.

f) Packaging

All components are housed in a plastic enclosure measuring 152.0 mm x 89.0 mm x 44.5 mm, which is molded of light high-impact ABS (acrylonitrile butadiene styrene). The two part enclosure consists of a base and cover section which are held together by screws entering through the base. Fixing points (stand-offs), for horizontal printed circuit board mounting, are included on each section. The physical layout of the display and control switches is shown in Figure 9.

On the top front cover of the case, a four-digit, seven-segment LED display is located, showing temperature to a tenth of a degree Celsius. The ferrite core antenna plugs into a connector located on the top to allow use of a remote probe for scanning of the subject's abdomen until a continuously audible signal is received. The three-digit thumbwheel switch on the bottom of the case is used to enter the calibration number of each pill. This ensures that absolute temperatures will be displayed on the readout.

A track-and-hold switch is incorporated on the right side which,while depressed, will update the displayed temperature. Once the switch is released, the last reading obtained will be displayed and held. The piezoelectric transducer used to produce the audio output is mounted on the side of the case. Power is supplied by a 9-volt battery which is installed in a compartment in the base of the case. The main power switch is located on the side below the track-and-hold switch.

USE OF THE RADIO PILL TEMPERATURE MONITOR

Radio pills can be used to measure temperature in either calibrated or uncalibrated modes. The calibrated mode is used when absolute temperatures are required. This involves calibrating the pill in a constant temperature bath at 37.0 °C and setting the thumbwheel switches to a value which will produce the proper temperature indication on the display. This calibration number is unique for each pill tested and must be set on the thumbwheel switches when the pill is used.

For the uncalibrated mode, only relative temperature changes may be obtained since the rates of change of RF bursts/sec with temperature are nearly identical for different pills (Figure 2). Since each pill transmits a different pulse frequency, the thumbwheel switches are used to set the indication of the temperature to a presumed initial starting point of 37.0 °C. It should be noted that when a pill is swallowed by a subject, a period of 30 minutes should be allowed for the pill to properly equilibrate to core temperature before this presumed starting value of 37.0°C is set. Proper notation of each calibration setting for individual subjects, whether absolute or relative, is necessary to monitor many subjects with one single unit.

The output of the radio pill is directional and, as the pill rotates during its passage through the gastro-intestinal tract, the signal strength varies at any given monitoring point. Hence, it is important to scan the abdomen region with the remote antenna until the maximum audible signal is produced by the piezoelectric transducer before the reading is taken.

DISCUSSION

The prototype Digital Temperature Monitor has been constructed and used extensively during a study of temperature rhythms in a sleep deprivation experiment. The digital display has higher resolution, better accuracy, less ambiguity due to range settings,and greater visibility than the original analogue meter (3,7). Orientation problems, which can be encountered with a meter-movement readout, are eliminated in the digital version. The plastic case of the monitoring unit provides an access cover for quick battery changes.

The antenna is an external probe and it provides convenience for scanning the subject's abdomen to obtain the maximum audible signal. The use of a track-and-hold switch allows the last temperature reading to be held until it can be recorded. Because of the digital nature of the device, no internal calibration is required and ambient temperature effects are reduced. The calibration switches can be used to directly offset the displayed temperature i.e., one switch setting for each tenth of a degree offset. However, the digital monitor is slightly more expensive to construct than the analogue version and also has a higher power consumption.

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FIGURE CAPTIONS

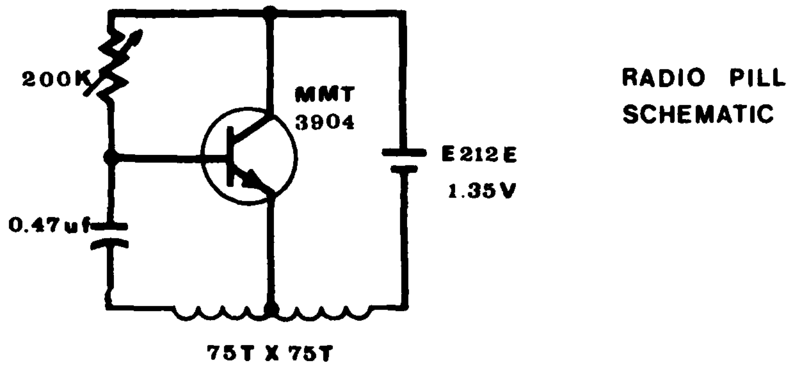


Figure 1. Circuit diagram for temperature-sensing radio pill

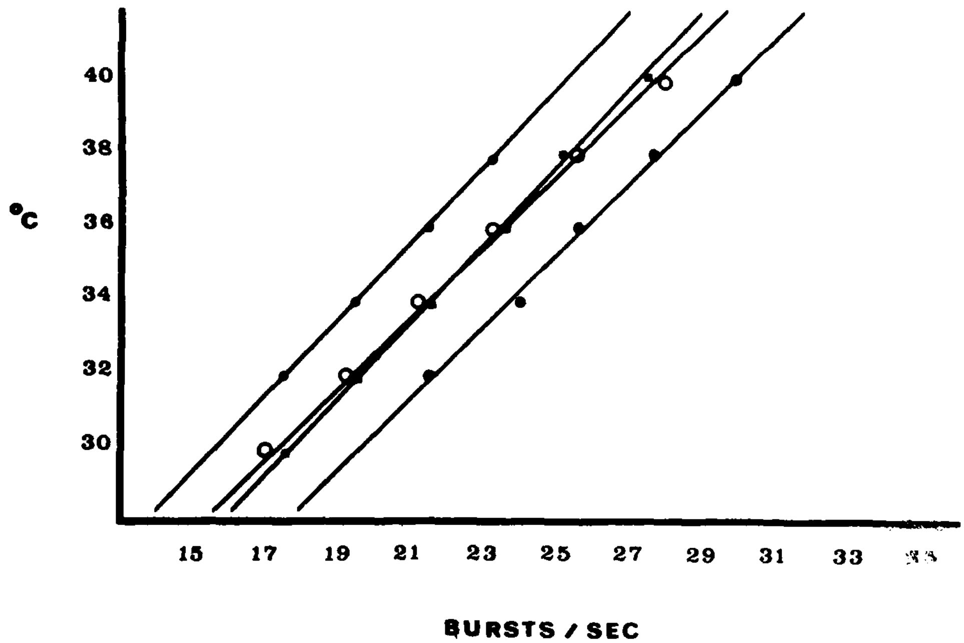


Figure 2. Sample calibration curves for temperature radio pills.

TEMP (°C)	BURST TIME (msec)
54.0	10.1
50.0	14.9
46.0	20.1
40.0	27.8
38.0	30.2
36.0	33.1
30.0	40.2
28.0	44.7
24.0	55.6
20.0	70.3
10.0	105.0

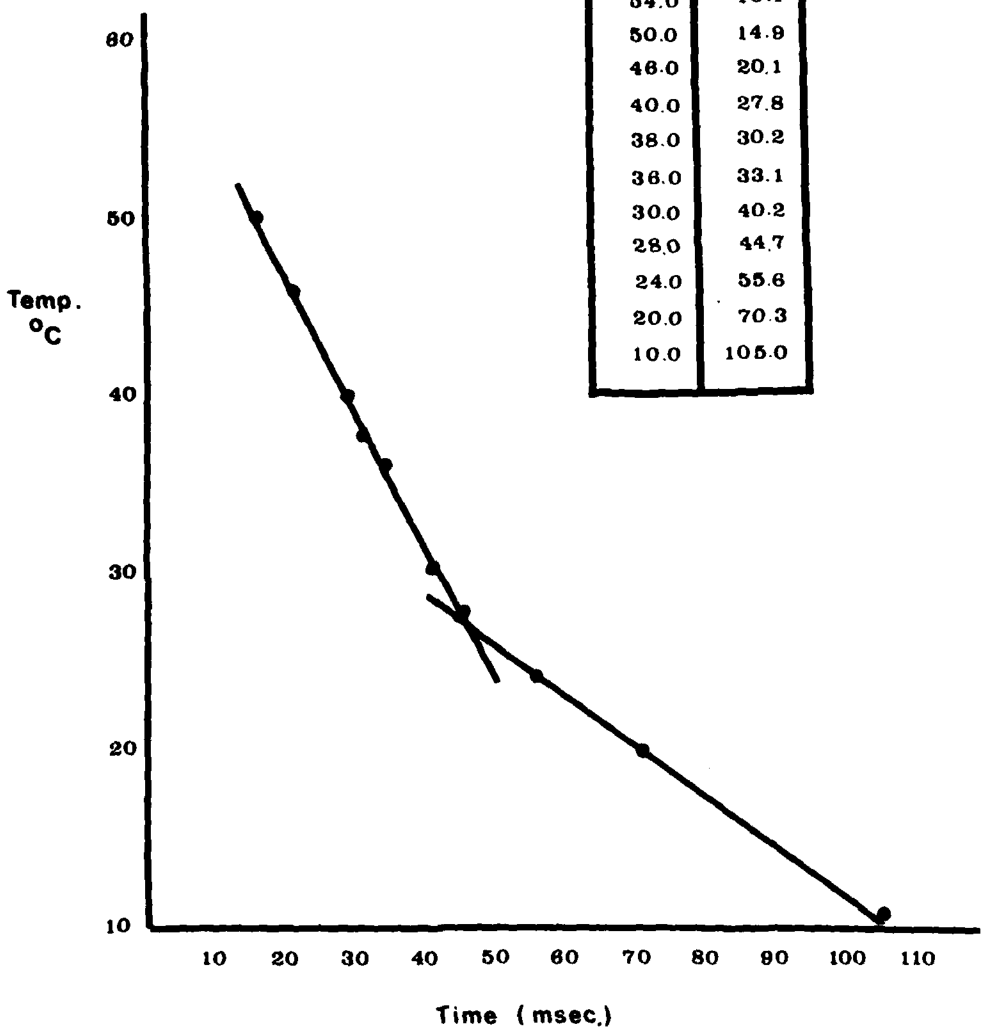


Figure 3. Graph of temperature vs burst period.

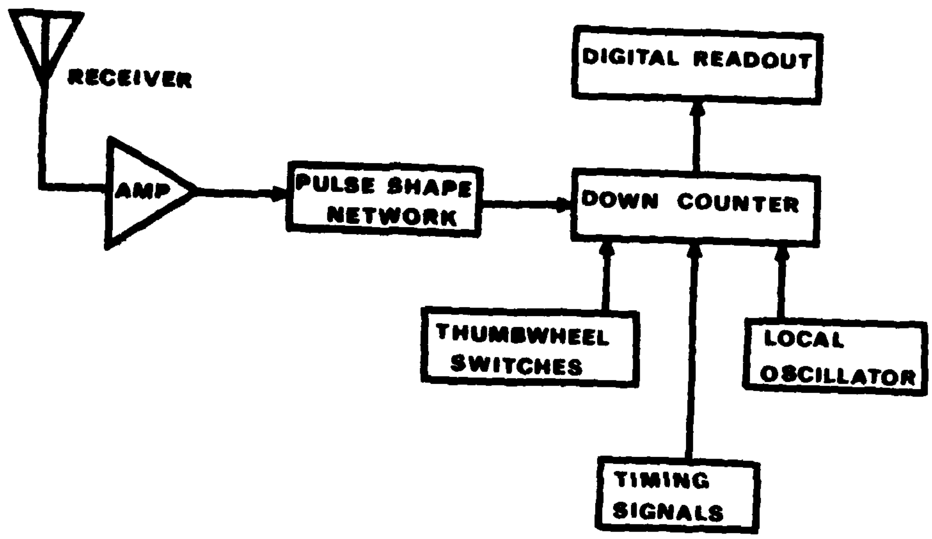


Figure 4. Block diagram of the digital radio pill monitor.

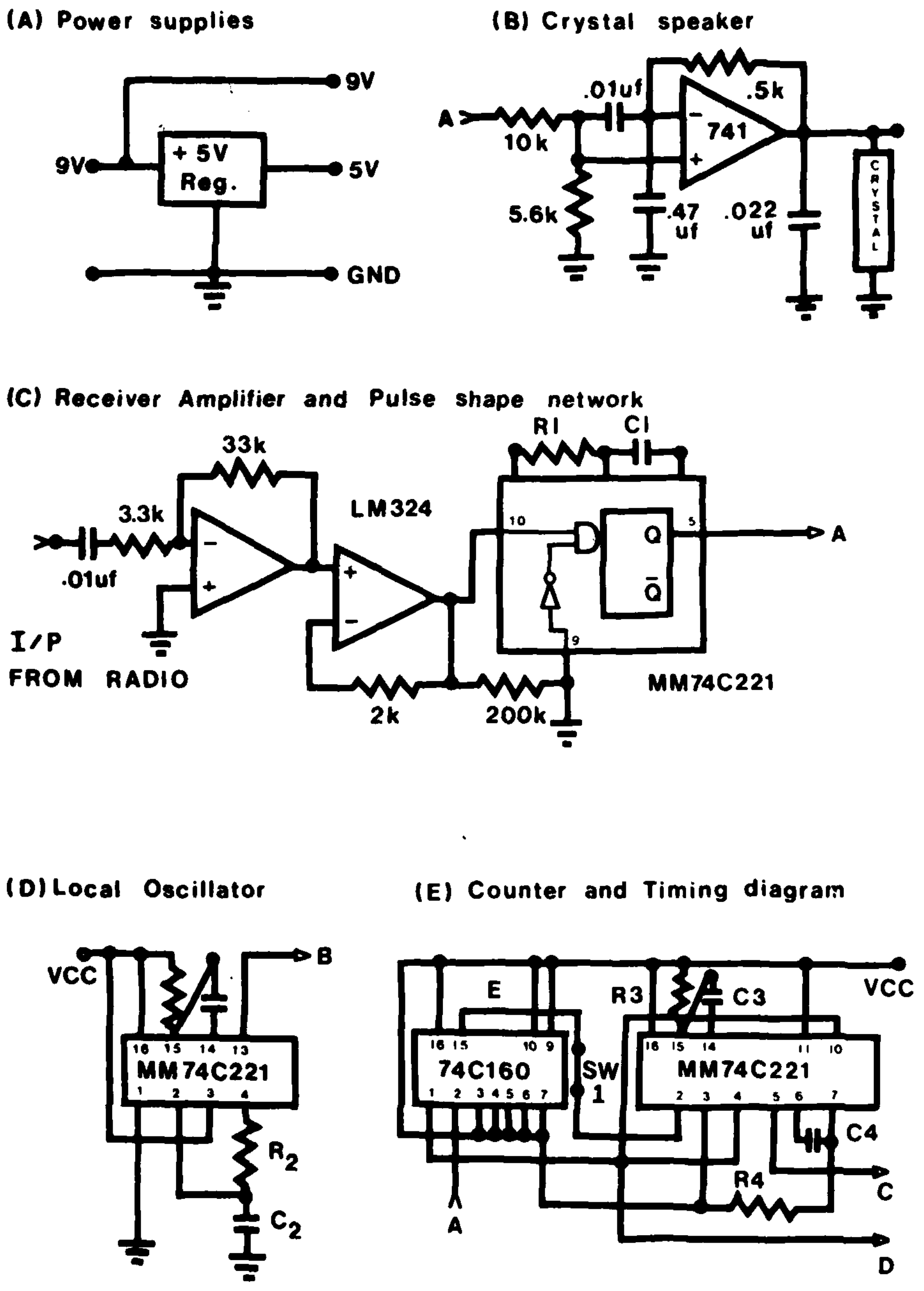
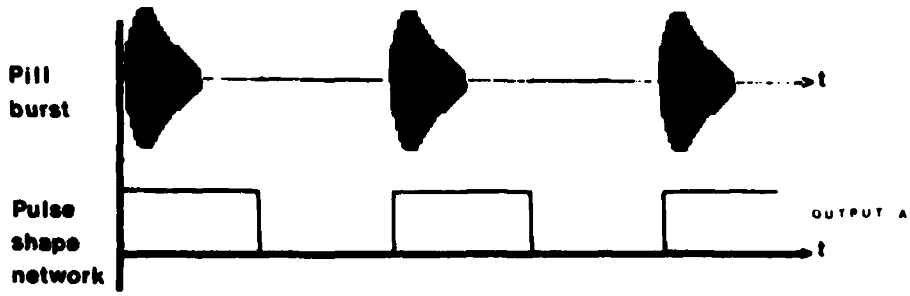
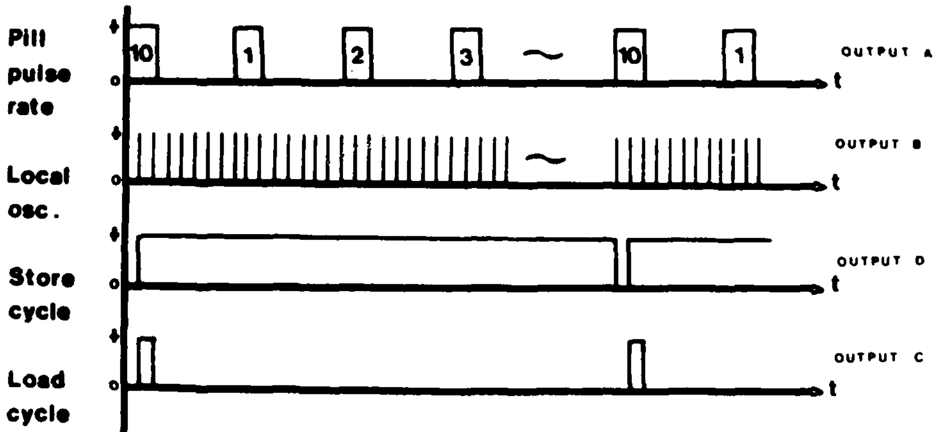


Figure 5. Circuit diagrams



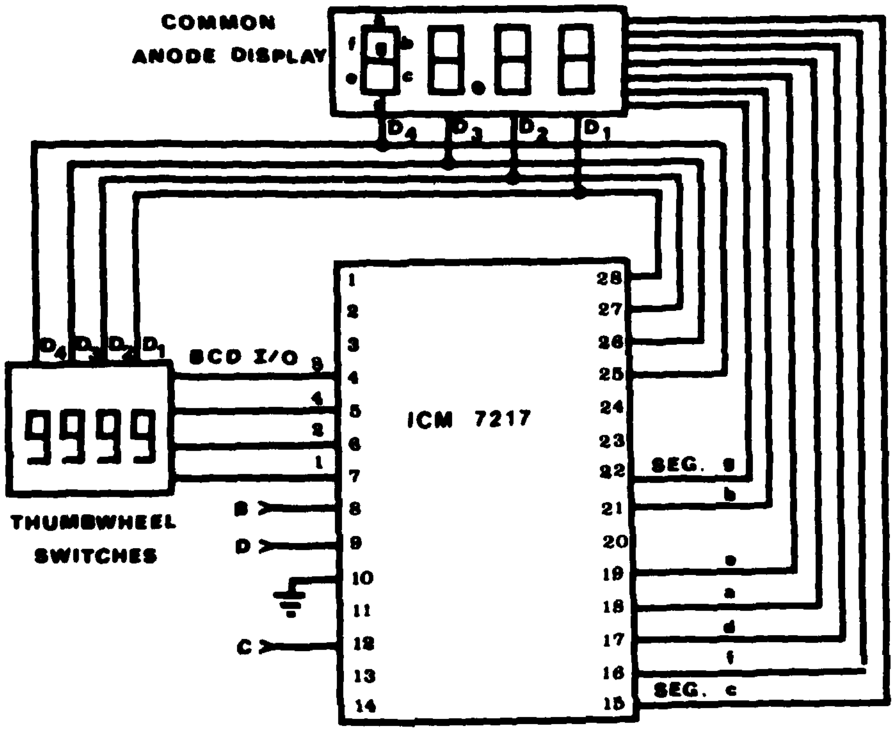
Pill
burst
t
Pulse
shape
network
OUTPUT A
t

FIG. 6



Pill
pulse
rate
10
1
2
3
10
1
OUTPUT A
t
Local
osc.
OUTPUT B
t
Store
cycle
OUTPUT D
t
Load
cycle
OUTPUT C
t

FIG.7



Thumbwheel switch / diode connection (common anode)

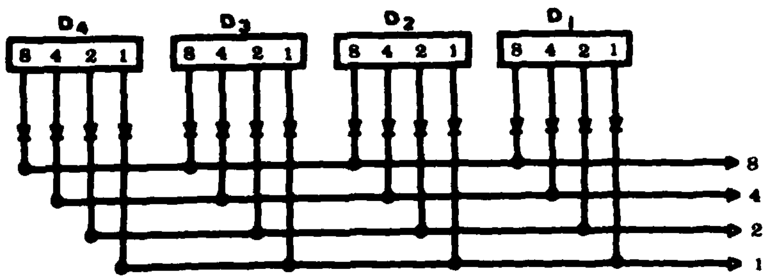
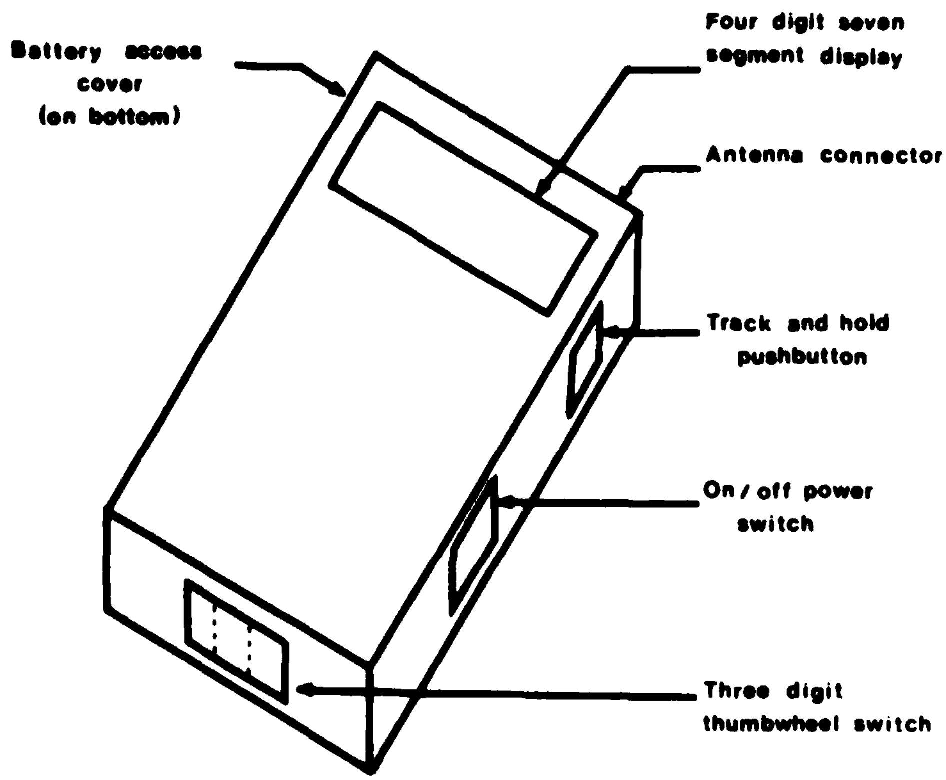


Figure 8. Circuit schematic of Intersil ICM 7217 Chip

TOP AND SIDE VIEW



Case dimension 6" x 3.5" x 1.75"
(152.0mm x 89.0mm x 44.5mm)

Figure 9. Display and control identification.